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Lensless Synthetic Aperture Chirped Amplitude-Modulated Laser Radar for Microsystems

by Barry Stann and Pey-Schuan Jian

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14. ABSTRACT

Future micro unmanned aerial vehicles and micro unmanned ground vehicles will require compact, low-cost, and low-power sensors for forming world maps of their surroundings for navigation and obstacle avoidance. These same sensors may also acquire, identify, and locate targets. This study examines an extremely simple laser radar design from a hardware standpoint that will form three-dimensional images of its surroundings while meeting the desired aforementioned attributes of a sensor for microsystems.

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1. Objective

Future micro unmanned aerial vehicles (UAVs) and micro unmanned ground vehicles (UGVs) will require compact, low-cost, and low-power sensors for forming world maps of their surroundings for navigation and obstacle avoidance. These same sensors may also acquire, identify, and locate targets. This study examines an extremely simple laser radar (ladar) design from a hardware standpoint that will form three-dimensional (3-D) images of its surroundings while meeting the desired aforementioned attributes of a sensor for microsystems.

2. Approach

The original Director's Research Initiative (DRI) proposal suggested using the U.S. Army Research Laboratory's (ARL's) patented chirped amplitude-modulated ladar architecture as the basic sensor for the microsystem to form images of a scene analogous to synthetic aperture radar (SAR). The following text will briefly describe the ARL ladar and explain how SAR imagery is formed.[1] In the ARL ladar, the transmitted light is amplitude modulated with a sinusoid that is frequency modulated according to a periodic linear ramp or sawtooth function. The light is broadcast over a broad beam that is perpendicular to the motion of the microsystem as shown in figure 1. A detector collects light backscattered over the illuminated region and converts it into an electrical signal. The light received from the target is delayed in time relative to the transmitted light, and an instantaneous frequency difference is observed between the transmitted modulation and the detector signals, which is proportional to range. By taking a sample of the original transmitted modulation signal and mixing it with the ladar's detector output signal, one recovers an intermediate frequency (IF) signal whose frequency is proportional to range. The Fourier transform of this signal determines the range to the target. A unique property of this ranging architecture is that the IF signal preserves the Doppler phase with respect to the mean modulation frequency and the distance between the ladar and the target. By repeatedly collecting IF waveforms as the microsystem travels along a straight path, a two-dimensional data set is formed that contains both range and Doppler information. The Doppler information contains azimuthal information, thus by using appropriate processing algorithms developed by the SAR community, the range and azimuth of the target can be determined.[2]

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[1]Stann, B. L.; Ruff, W. C.; Sztankay, Z. G. Intensity-Modulated Diode Lasar Radar Using Frequency Modulation/Continuous Wave Ranging Techniques. *Optical Engineering* **1996**, *35* (11), 3270–3278.

[2]Harger, R. O. *Synthetic Aperture Radar Systems: Theory and Design*; Academic Press: New York, 1970.

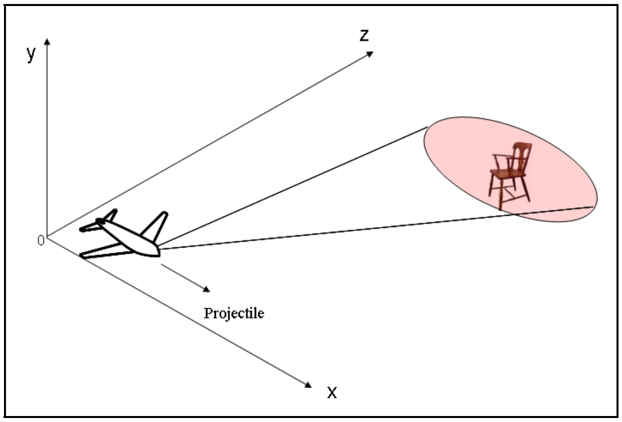

Figure 1. Microsystem operational scenario.

In the usual SAR scenario, the system ranges to several kilometers and collects IF data continuously over a straight flight path. To form an image line along any position on the flight path, data collected over the low hundreds of meters (called an aperture) must be processed to obtain azimuthal resolutions around 30 cm. To illuminate a scatterer over this aperture, the illumination field of the SAR must subtend 1° to 3°. The scenario for the microsystem is substantially different because operation is expected in enclosed spaces where range to the target is short. Here the aperture can be a larger fraction of the target range, and the illumination field may subtend 30º or more. Because of this difference, the Doppler waveform changes strongly with range to the target. Figure 2 supports this notion by showing significant changes in the Doppler waveform as a function of target distance for an illumination field spread over 30º. This suggests that the Doppler waveform in the microsystem scenario may contain sufficient information to form 3-D images without applying frequency modulation to the light modulation.

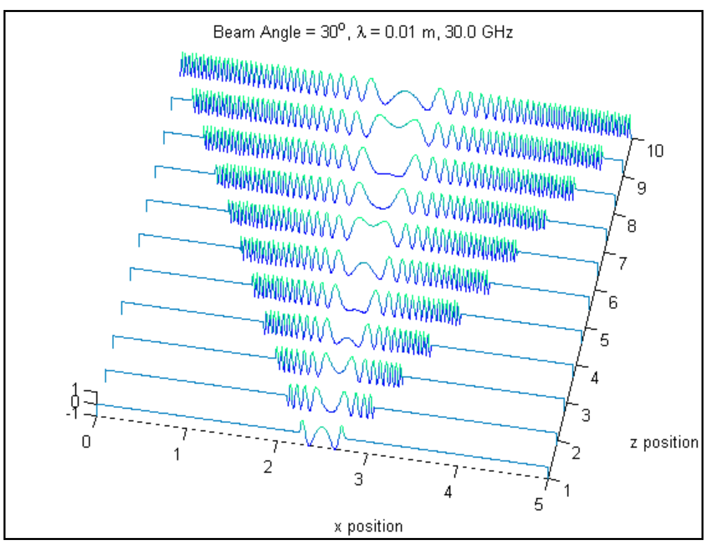

Figure 2. Doppler waveforms as a function of distance to target.

Because of this observation, the authors decided to begin the study by analyzing a synthetic aperture (SA) ladar imager that only uses the Doppler information to form 3-D images. This has several advantages. For one, the frequency modulation function is eliminated, which represents a significant reduction in the amount and complexity of hardware carried by the microsystem, and power consumption is reduced. The Doppler-only ladar also reduces the amount of data that must be acquired, stored, and transmitted to the ground by roughly 2 orders of magnitude. The bandwidth of the data acquisition system is also reduced by the same factor.

A block diagram of the SA ladar is shown in figure 3. Here a microwave oscillator operating in the 18 to 30-GHz range drives an amplifier that, in turn, amplitude modulates a low-power laser diode. Light from the laser facet is collected by an optical system that directs the light into a wide illumination field, say, for example, 30° × 30°. A small lens system collects light backscattered from the illuminated target region and focuses it onto a wide bandwidth detector that converts the light into a current. To recover the Doppler signal, the amplified photo-current is fed into a mixer driven by the original laser modulation signal. The Doppler signal is further amplified and sampled with an analog-to-digital converter. The digital data is fed into a computer for processing to form imagery.

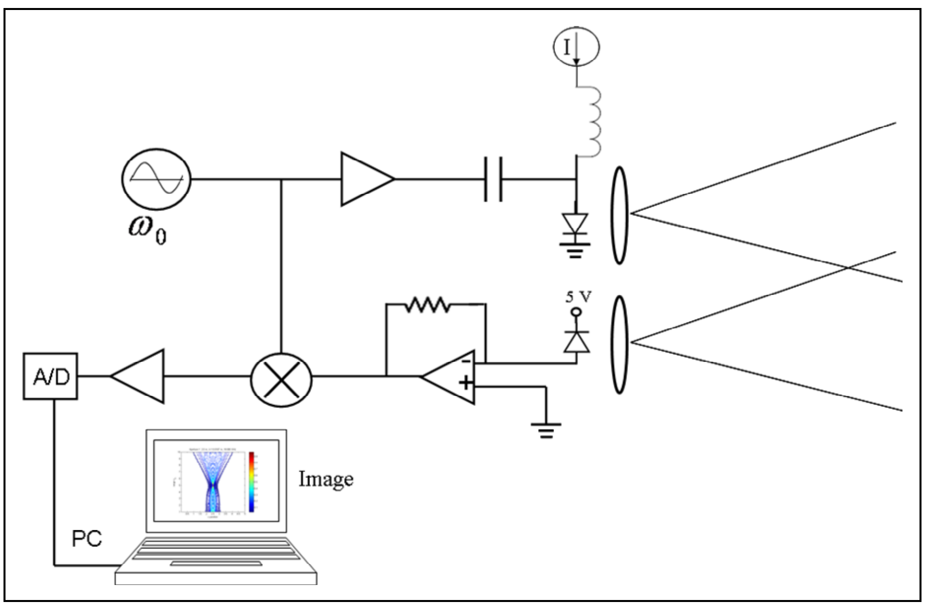

Figure 3. Block diagram of the SA ladar.

The SA ladar system was modeled to determine if sufficient signal-to-noise is attainable using presently available components. The ladar was required to form images with 0.25-m azimuthal resolution in the horizontal and vertical dimensions at 10 m from the flight path. The field of regard for the system was 30º × 30º, which meant that the system would successively form line images 20 pixels (or 5 m) high in the vertical dimension at 10 m while continuously collecting data from horizontal lines of 20 pixels. The amount of power allotted to each pixel is then 1/400

of the total power in the illumination field. Presently, fiber-coupled 1.55-µm diode laser sources are sold yielding powers of 0.5 W; therefore, 1 mW of illumination power is allowed to each pixel. Other key system parameters include a receive aperture diameter of 5 mm, an integration time of 1 s, and a detector responsivity of 10 (Avalanche detectors with this responsivity at 1.55 µm are commercially available). The system calculations yielded a signal-to-noise of roughly 30 for targets at 10 m in range and with a reflectivity of 1. Other embodiments of the system may perform mixing with an electro-optic light modulator in the receive path. In this design, more sensitive detectors (perhaps Geiger mode detectors) may be used, allowing reduced illumination power.

3. Results

In the following analysis, the point spread function is computed for the SA ladar, assuming that the ladar flies a straight path along the X axis and the illumination and receive field of view overlap and encompass the single point scatterer at (X_1, Y_1, Z_1) as shown in figure 4. The photodetector recovers a current that is mixed with a sample of the original modulation signal to recover the Doppler waveform. For this simulation, it is assumed that the SA ladar uses a quadrature mixer that consists of two mixers where the local oscillator ports are fed with quadrature signals, cosine(ω_0t) and sine(ω_0t), to recover both in-phase (*Re*) and 90° out-of-phase (*Im*) Doppler signals, respectively. The expressions for the two Doppler signals derive from the expression for the distance between the sensor and the scatterer as a function of the sensor position on the X axis, $R(x(t))$.

$$R(x(t)) = \sqrt{[x_1 - x(t)]^2 + y_1{}^2 + z_1{}^2} \quad . \tag{1}$$

It follows that the real and imaginary Doppler signals are then

$$\mathrm{Re}(V(t)) = \cos(\frac{4\pi}{\lambda} R(x(t))) \tag{2}$$

and

$$\mathrm{Im}(V(t)) = \sin(\frac{4\pi}{\lambda} R(x(t))) \,. \tag{3}$$

Samples of the real and imaginary Doppler signals are shown in the left-hand side of figure 4.

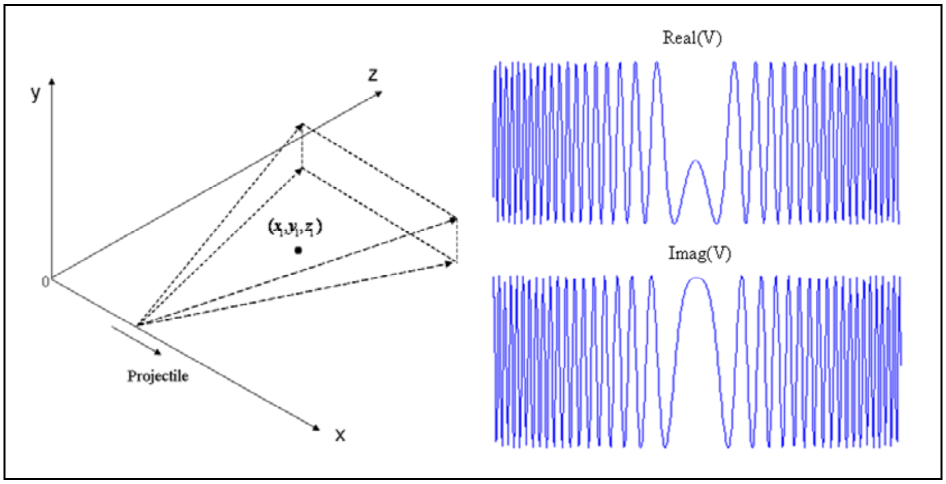

Figure 4. Modeled SA ladar scenario and *Re* and *Im* Doppler waveforms.

To compute the point spread function (PSF) for this scenario, the authors computed the *Re* and *Im* (i.e., complex) Doppler waveforms constrained by the ladar's field of regard for 500 scatterer positions within the region 0 < Z < 10 m. This created a basis set that could be numerically correlated against the Doppler waveform from (X_1,Y_1,Z_1) for 620 positions over the region 0 < X < 5 m. The ladar's field of regard was simulated to look perpendicular to the flight path and over a 30º angle, which would be typical of the ladar's optical system. The wavelength of the modulation was 1 cm, corresponding to a frequency of 30 GHz. Figure 5 shows the results of the correlation as a contour plot that is maximum at the target position (X_1, Z_1) = (2.5 m, 5 m). The 6-dB points on the PSF are 2.5 cm in the X direction and 0.52 m in the Z direction. Figure 6 shows the PSF for three targets at (X_1, Z_1) = (2 m, 2 m), (X_1, Z_1) = (2.5 m, 5 m), and (X_1, Z_1) = (3 m, 7 m). Note that the resolution in X is roughly constant in Z, but the Z resolution becomes lower with increases in Z.

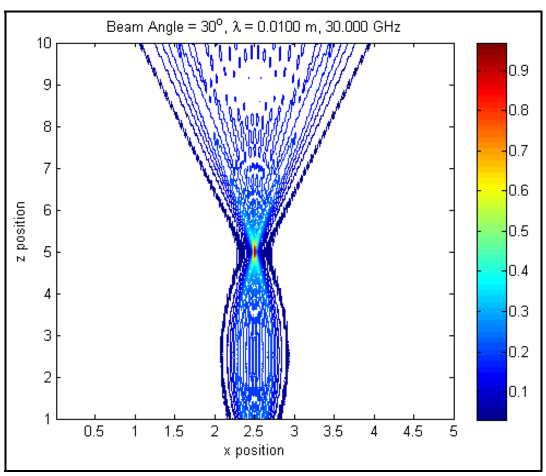

Figure 5. Correlation map on X-Z plane.

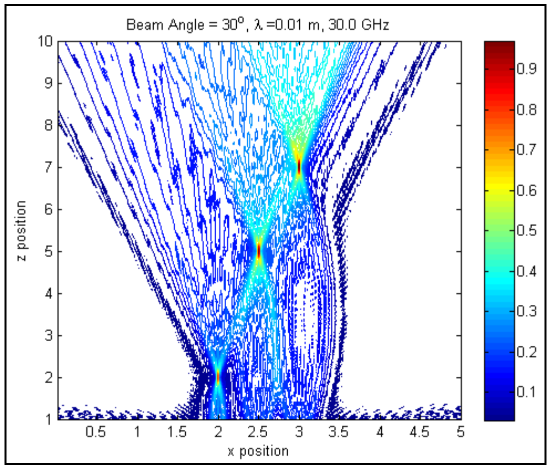

Figure 6. Correlation map with three targets.

These results demonstrate that the Doppler waveform contains sufficient information to recover the Z position of a scatterer. However, the mathematical process is ambiguous circularly around the X axis and thus will not produce a useful image for the microsystem. If the microsystem travels a curved path in a plane, then sufficient information may be available to form 3-D images. This situation is examined in the following text.

To explore resolving a scatterer in all three dimensions, the expression for the distance to the scatterer is revised to include motion of the SA ladar in the Y dimension. $R(x(t))$ is now

$$R(x(t)) = \sqrt{[x_1 - x(t)]^2 + [y_1 - y(x(t)]^2 + z_1{}^2} \quad , \tag{4}$$

where the ladar follows a sinusoidal path in the X-Y plane given by

$$y(x(t)) = (0.7 + \sin(x(t) \bullet \pi / 4) \bullet 1.25 \quad . \tag{5}$$

As for rectilinear ladar motion, the authors computed the *Re* and *Im* Doppler signals corresponding to a point scatterer at (2.5, 2.5, 5). The field of regard was also modeled to extend over angles in two dimensions, 30º × 30º, and constrained its pointing direction to look perpendicular to the X axis and parallel to the Z axis. As previously noted, the modulation wavelength was 1 cm, corresponding to a frequency of 30 GHz. The complex basis set was computed over the region 0 < X < 5 m, 0 < Y < 5 m, and 1 < Z < 8 m with the number of points limited to 256 in each dimension and performed the numerical correlations against the Doppler signal for the point scatterer. This process required about 1 hr of time on a 2.39-GHz Pentium computer with 2 GB of RAM. The result is plotted in figure 7, which shows the PSF projected into the Y-Z plane at X = 2.5. The 6-dB points on the PSF are 2.2 cm in the X direction, 10.5 cm in the Y direction, and 17.2 cm in the Z direction. For reference, the flight path of the SA ladar is drawn on a respective coordinate system just below the plot for the PSF.

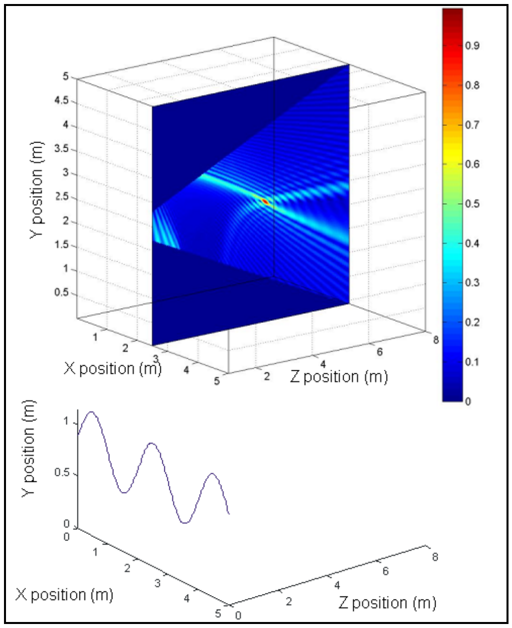

Figure 7. Correlation map in Y-Z plane at x = 2.5 m with SA ladar on a sinusoidal trajectory.

4. Conclusions

In conclusion, the SA ladar simulation shows that a system relying on minimal hardware but high computational requirements may adequately form imagery for micro UAVs and possibly micro UGVs. Relatively large swaths of 3-D imagery within the field of regard for the ladar are formed by sampling and processing only about 51 points/m of travel in the X dimension. This is a considerable savings over the ~3000–5000 sample points/m required by the use of the classical strip map SAR approach originally proposed for this DRI.

Other work comes to mind to further validate this imaging scheme. This may include analyses to investigate 3-D SA ladar flight paths, squinting the field of regard forward to form imagery ahead of the microsystem, and data weightings to lower PSF sidelobe levels. The system must rely on data from a compact, low-power, and accurate inertial navigation system (INS) to generate the basis functions. A review of the state-of-the-art on new microelectromechanical systems INSs is appropriate, including an analysis of how INS errors can defocus the image. Finally, researchers should build an SA test probe and fly it along a constrained path, collect data, and form imagery to evaluate the concept experimentally.

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